

Testing the Dipole and Quadrupole Moments of Galactic Models

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INTRODUCTION

If gamma-ray bursts originate from a galactic source population, then at some level a galactic pattern must exist in their locations. Expected patterns for galactic sources are a concentration towards the galactic center, measured by the mean dipole moment of the locations towards the center, $\langle \cos \theta \rangle$, where the θ_i are the angles between the burst locations and the galactic center, or a concentration towards the galactic plane, measured by the mean quadrupole moment about the plane, $\langle \sin^2 b - \frac{1}{3} \rangle$, where the b_i are the galactic latitudes of the locations (23,2). To date, neither pattern has been found in the BATSE data: the values $\langle \cos \theta \rangle = 0.011 \pm 0.017$ and $\langle \sin^2 b - \frac{1}{3} \rangle = 0.002 \pm 0.009$ (these values have been corrected for BATSE's nonuniform sky exposure) for the 1122 bursts of the 3B catalog are both consistent with zero and thus with isotropy (21). The dominant uncertainty in these values is due to the finite sample size (4). What galactic signatures could be hidden under these uncertainties?

The tight limits on the quadrupole moment, in conjunction with the fall-off in the number of faint sources, rule out a disk origin for the majority of the sources (20,9,3,4). Galactic models which remain under discussion either consist of an extended halo or of multiple components. A halo consistent with the data must be much larger than the solar galactocentric distance of $R_\odot = 8.5$ kpc so that the dipole moment will be sufficiently small. We can determine the typical scale by considering a very simple halo: a galactocentric

shell of radius R_{shell} . Such a shell has a dipole moment (13):

$$\langle \cos \theta \rangle = \frac{2}{3} \frac{R_o}{R_{\text{shell}}}. \quad (1)$$

Using the dipole moment of the 3B catalog (above), we obtain a 2σ lower-limit for R_{shell} of 120 kpc. Any GRBs inside of this radius will have to be balanced with sources located farther away.

In the remainder of this paper we compare galactic models which have published moments with the observed moments of the 3B catalog. The procedures and the models are discussed in greater detail in an earlier work, which used a smaller sample of GRBs (4).

GALACTIC MODELS

The models with quantitative moments that we are aware of appear in Table 1. For each model we list in the table all moments meaningfully different from zero. Each model listed has one or two such moments. In some cases the parameters of the published model are based on fits to the then existing GRB sample; conversely the parameters of some models are not based upon fits but are (presumably very good) examples of the model. We have merely extracted the model moments from the publications—we have made no effort to reoptimize the models. Since in most cases the models have free parameters and were created when the BATSE GRB sample was smaller, rechoosing the parameters might improve agreement with the data. In some cases, a full refitting might worsen agreement because of the tightened constraints on the brightness distribution, logN-logP.

From the table it is apparent that while some galactic models are quite inconsistent with the observed moments, others agree well. The best (and most recent) model (5) is within 0.3σ of the observed dipole moment. The model (19) most distant from the data deviates by 4.0σ from the observed dipole moment and 6.9σ from the observed quadrupole moment. There is an approximate trend for the moments of the more recent models to be smaller, as additional data from BATSE has indicated that the moments of the first post-BATSE models were too large.

Of the models including a disk component (19,27,14,28), the one that best matches the data is the Dark Matter Halo/Disk model of Smith & Lamb (27), which has a 2.7σ deviation in $\langle \cos \theta \rangle$. The largest moment in this model is the dipole moment of its halo component, since only 20% of the bursts originate from the disk component.

The remaining models all assume that GRBs originate from an extended halo. These models fall into two classes: arbitrary models which postulate a source radial distribution and high-velocity neutron star (HVNS) models which assume that the halo consists of HVNS ejected from the disk. The HVNS models have the advantage of being based upon plausible sources and

TABLE 1. Moments of Galactic Model Compared with the Observations

Model	Statistic	Prediction ^a	Dev. ^b
Eichler & Silk (7)	$\langle \cos \theta \rangle$	0.05	2.3
Hartmann (12)	$\langle \sin^2 b - \frac{1}{3} \rangle$	-0.05	5.8
Li & Dermer (16)	$\langle \cos \theta \rangle$	0.048	2.2
Lingenfelter & Higdon (19)	$\langle \cos \theta \rangle$	0.08	4.0
	$\langle \sin^2 b - \frac{1}{3} \rangle$	-0.06	6.9
Fabian & Podsiadlowski (8)	$\langle \cos \theta_{\text{LMC}} \rangle$ ^c	0.038	1.4
Smith & Lamb (27): Disk/Gaussian Shell Halo	$\langle \sin^2 b - \frac{1}{3} \rangle$	-0.027	3.2
Smith & Lamb (27): Dark Matter Halo/Disk...	$\langle \cos \theta \rangle$	0.057	2.7
Higdon & Ling. (14): $R_{\text{core}} = 7.5$ kpc, 25% disk	$\langle \cos \theta \rangle$	0.088	4.5
Higdon & Ling. (14): $R_{\text{core}} = 15$ kpc, 20% disk	$\langle \cos \theta \rangle$	0.073	3.6
Higdon & Ling. (14): $R_{\text{core}} = 30$ kpc, 8% disk	$\langle \cos \theta \rangle$	0.060	2.9
Li, Duncan & Thompson (17) ^d	$\langle \sin^2 b - \frac{1}{3} \rangle$	-0.084	1.8
	$\langle \cos^2 \theta - \frac{1}{3} \rangle$ ^e	0.073	2.6
Podsiadlowski, Rees & Ruderman (26): Fig. 5a	$\langle \cos \theta \rangle$	0.043	1.9
	$\langle \sin^2 b - \frac{1}{3} \rangle$	-0.019	2.3
Podsiadlowski, Rees & Ruderman (26): Fig. 5b	$\langle \cos \theta \rangle$	0.054	2.5
	$\langle \sin^2 b - \frac{1}{3} \rangle$	-0.024	2.9
Smith (28)	$\langle \cos \theta \rangle$	0.050	2.3
	$\langle \sin^2 b - \frac{1}{3} \rangle$	-0.023	2.8
Bulik & Lamb (5)	$\langle \cos \theta \rangle$	0.016	0.3

^aNot corrected for BATSE's nonuniform sky exposure.

^bDeviation, in σ , of the prediction from the value observed for the 1122 bursts of the 3B catalog (expect 109 bursts for Li et al. (17)). Includes correction for sky exposure.

^cStatistic is the dipole moment to the Large Magellanic Cloud; the observed value is -0.010 and the predicted sky exposure bias is -0.024.

^dThe predictions are for bursts with 1024 ms peak flux $> 3.45 \gamma \text{ s}^{-1} \text{ cm}^{-2}$, of which there are 109 in the 3B catalog.

^eThe observed value of this quadrupole moment is -0.005 and the sky exposure predicted value is -0.004.

incorporating more physics, but have potential difficulties explaining why only HVNS burst and whether there are sufficient HVNS to produce the observed burst rate.

The models (7,12,14) which postulate a source distribution usually assume a dark matter halo form, following the example of Paczyński (24). To match the data, these models are driven to very large core radii, larger than assumed in dark matter models of the galactic rotation curve and larger than any observed galactic component (4). Also suggested are a Gaussian shell halo (27) and a exponential halo (27,28), both of which differ from any known galactic population.

The first HVNS model (16) is still in acceptable agreement with the data, probably because of the 1000 km s^{-1} velocity assumed for all of the bursting sources, a higher value than used by more recent versions of this model. The most recent HVNS model (5) closely matches the data. The unusual model of Fabian and Podsiadlowski (8) is also in good agreement with the data despite using an unusually low source velocity, 400 km s^{-1} . This is achieved by the unique assumption that GRB sources are born only in the Magellanic Clouds, so that the sources are born at halo distances and can easily escape their birth site. However, if sources are born in the disk of the Milky Way at even a small fraction of the Magellanic Cloud birth rate per mass, a strong disk signature would be produced.

Since the uncertainties on the observed moments decrease as $1/\sqrt{N_B}$, where N_B is the number of burst locations in the sample, further progress in testing the moments of galactic models will be slow. Collecting additional data still has several important benefits: it will tighten the constraints on galactic models and aid in analyzing suggested sub-classes of bursts (1,15,25). The tightened limits on the properties of a hypothetical Milky Way halo will aid in interpreting proposed observations of the corresponding halo of M31, observations which are intended to distinguish between halo and cosmological distance scales (6,10,11,18,22).

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